Fast and Accurate Simulations of Proto-planet Migration in Disks

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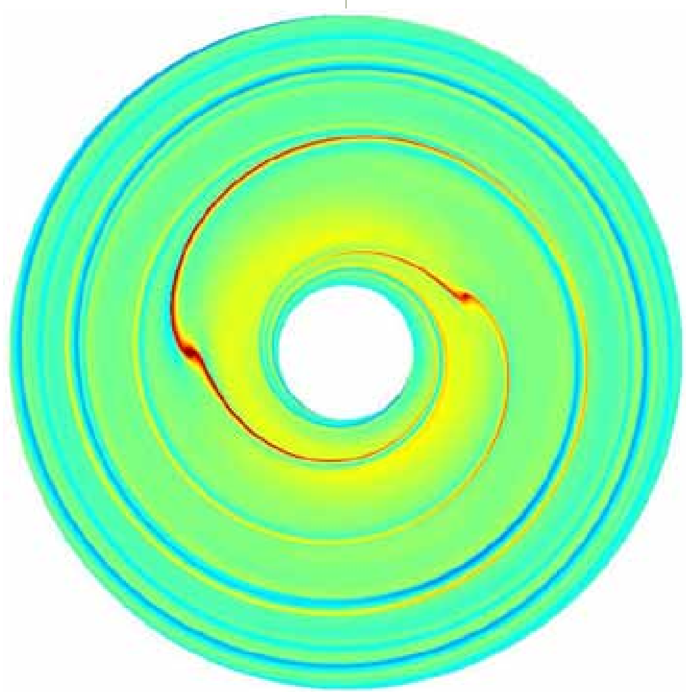
More than 400 extra-solar planets have been discovered since the first discovery in 1995. Planets are believed to form from the protoplanetary disks of gas and dust that are observed to orbit young stars. Once formed, planetary orbits may be modified as a result of gravitational tidal interactions with their nascent gaseous disk. This interaction can result in planetary migration (e.g., moving towards the parent star), directly threatening the survivability of protoplanets and altering their orbits. One of the primary challenges in this field is to understand the observed orbital properties of the more than 400 planets discovered that show marked differences from our own Solar system.

Fig. 1. Density plot for the tidal interaction between the disk and the embedded proplanets.



The interaction between the disk and planets (see Fig.1) is difficult to simulate. First, it requires an integration time up to thousands of orbits and millions of simulation time steps to obtain results that are insensitive to the initial conditions [1]. Second, it involves many physical processes that are represented either by partial differential equations with discontinuities for the disk or by ordinary differential equations for the planets. The disk motion and the planet motion must be coupled tightly to obtain an accurate estimation of the torque exerted on the planet. Third, it requires a very high-resolution mesh, especially for the case of the high-mass planet, to resolve the near-planet region and the co-orbital region [2].

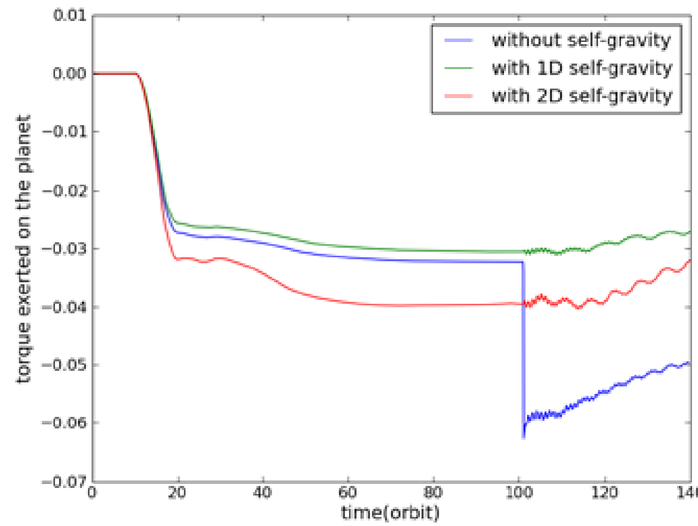


Figure 2. The impact of the disk self-gravity on torque exerted on the planet.

Thanks to the FARGO, fast advection in rotating gaseous objects, algorithm [3], we can simulate the interaction between the disk and planet using a fine-resolution grid for a long time. We have observed that FARGO is at least an order of magnitude faster than other standard solvers. We have modified the original FARGO so that it becomes more efficient and accurate [4].

The self-gravity of the disk is important in estimating the torque exerted on the planet. Without self-gravity, the coupled system is treated inconsistently because the planet is subject to the gravity of the disk, whereas the disk itself is not. We have implemented a full 2D self-gravity solver on a uniform disk grid [5]. This solver uses a mode cut-off strategy to reduce the computation and the communication between different processors in parallel computing. The algorithm is sufficiently fast that the self-gravity solver costs less than 10% of the total computation cost in each run. Figure 2 shows the difference on torque estimation with and without disk self-gravity.

The planet motion requires a smaller time step than that of the disk motion. During one disk motion time step, the planet motion is calculated with high-order time integrations and controlled in a subcycling fashion by moving within a 0.05 grid spacing in each substep. The disk gravitational force on the planet, which is calculated whenever the disk and planet move to the same position in the azimuthal direction, is assumed to evolve linearly with time during these substeps. To enhance the resolution near the planet, we developed and implemented an embedded Lagrangian adaptive mesh refinement (AMR) for the FARGO-type solver. Unlike traditional AMR, our local refinement can move across several cells in the azimuthal direction in one time step. This combination of AMR with FARGO speeds up our computation by another order of magnitude.

The simulation is 2D but includes a prescription to approximate the effects of 3D when calculating the gravitational force from the disk material. This is accomplished by spreading the surface density of a given cell vertically in a Gaussian profile. With this pseudo-3D treatment migration rates from simulations with sufficient viscosity—dimensionless kinematic viscosity (1E–6) agrees well (within a few percent) with the 3D linear theory results of Tanaka et al. [6].

We have used our code to study the Type-I migration rate for the low-mass planet [1]. We found that Type-I planet migration can be halted in disks of sufficiently low turbulent viscosity. We have also applied the code to study the Type-III migration, and found that run-away migration is possible under certain circumstances [7].

For a relatively high-mass planet and disk with low or zero viscosity, we found that the shock-induced vortices can be generated in the disk (see Fig. 3). These vortices greatly affect the planet migration rate and even lead to gravitational instability.

The code is fully parallelized with a message-passing interface (MPI) and is verified using the published examples. More details about the algorithm and its numerical experiments can be found in [4].

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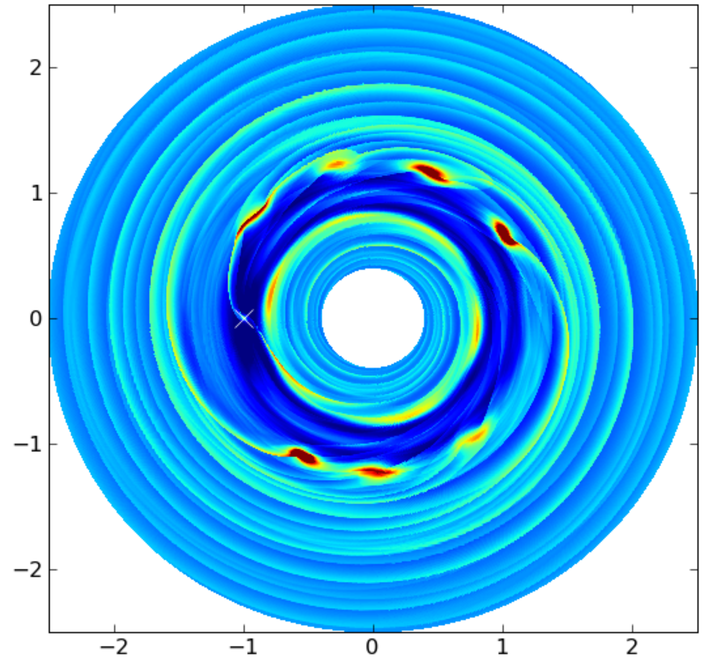

Fig. 3. The impact of viscosity on the planet migration rate.

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